

# Rare Decays at B Factories

Recent Results from BaBar and Belle

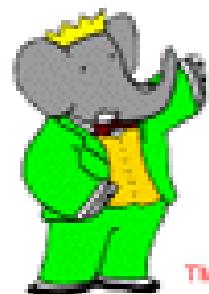
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Yury Kolomensky

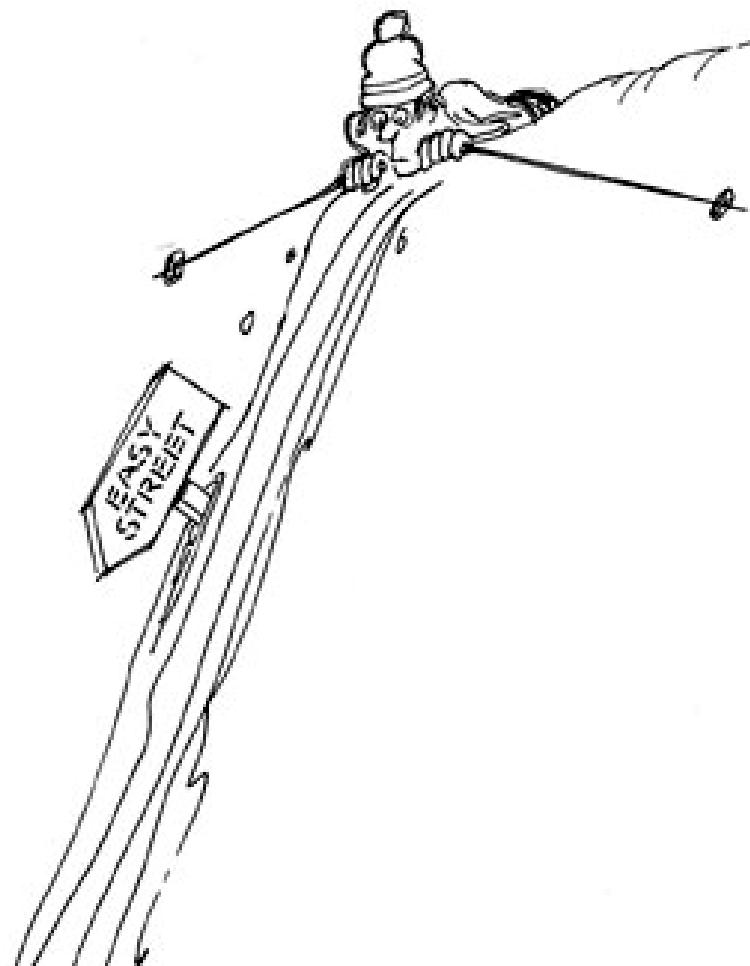
UC Berkeley/LBNL

2004 Aspen Winter Conference on Particle Physics

February 5, 2004



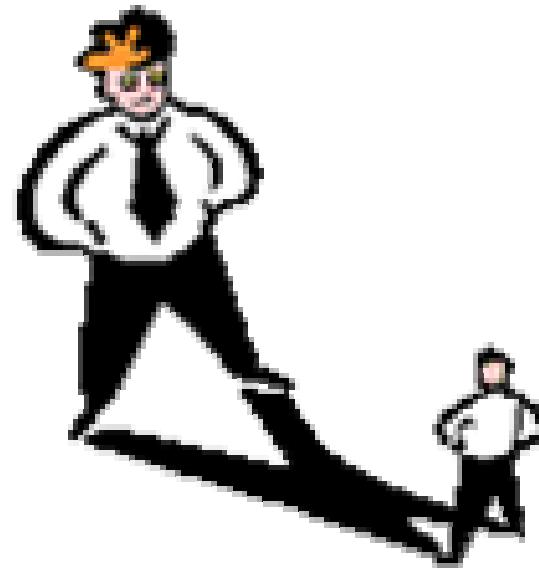
# Where We Are and Where We Are Going



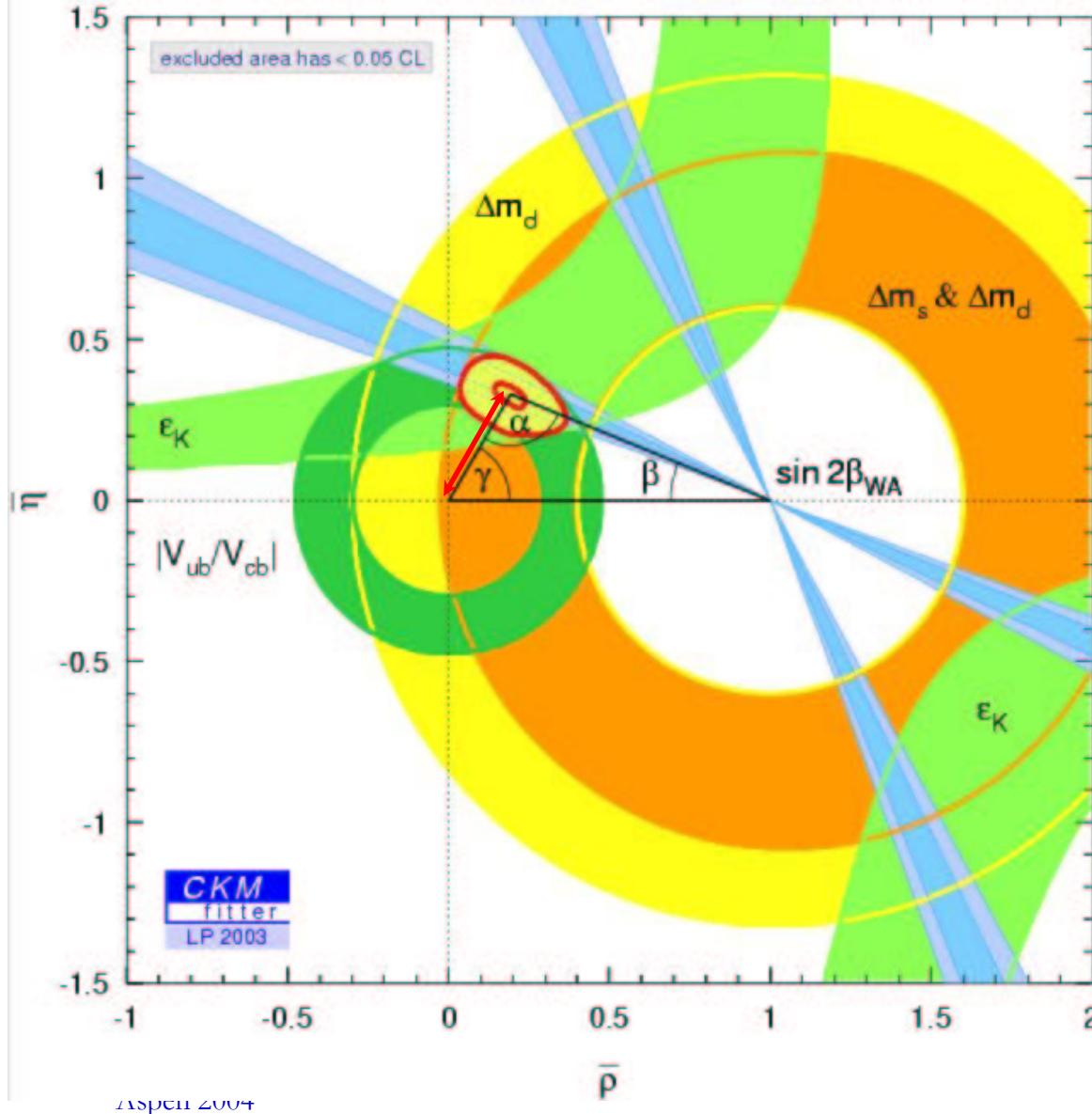
# Outline

- ☞ General theme: explore high statistics of the B factories to (indirectly) probe new physics at high energy scales
  - New analysis techniques
  - Sensitivity to highly suppressed modes
- CKM physics:  $V_{ub}$  via inclusive B decays
- Loops: Electroweak Penguins
- Highly suppressed modes: Leptonic B decays
- Conservation laws: LPV in tau decays

# Inclusive $V_{ub}$ Measurements



# Status of CKM Unitarity Triangle



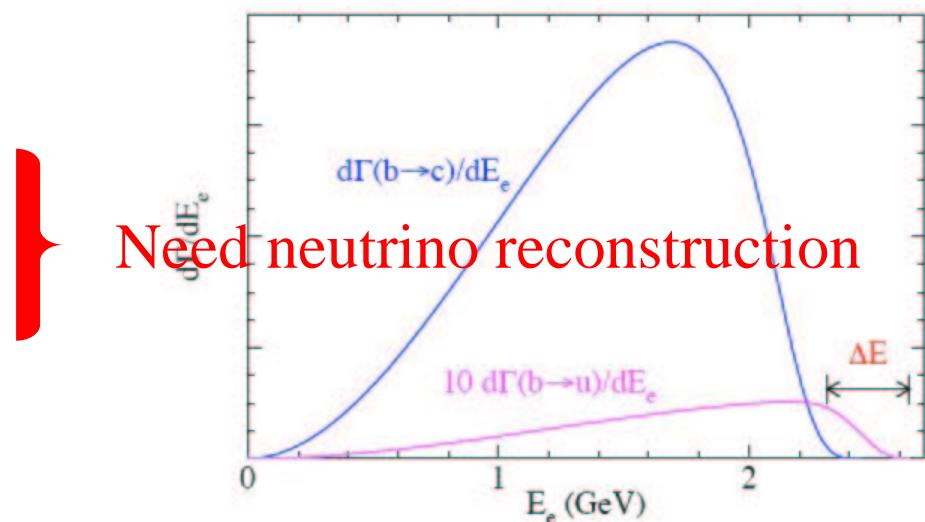
- $V_{ub}/V_{cb}$  an important constraint
- Important to achieve precision of  $\sim 5\%$
- ☞ New theoretical and experimental developments make this possible

# $V_{ub}$ via Inclusive Rates

- Theoretically clean determination of  $V_{ub}$  from inclusive rates

$$|V_{ub}| = (3.04 \pm 0.06_{(pert)} \pm 0.08_{(mb)}) \times 10^{-3} \left( \frac{B(B \rightarrow X_u \ell \bar{\nu})}{0.001} \frac{1.6 \text{ ps}}{\tau_B} \right)^{1/2}$$

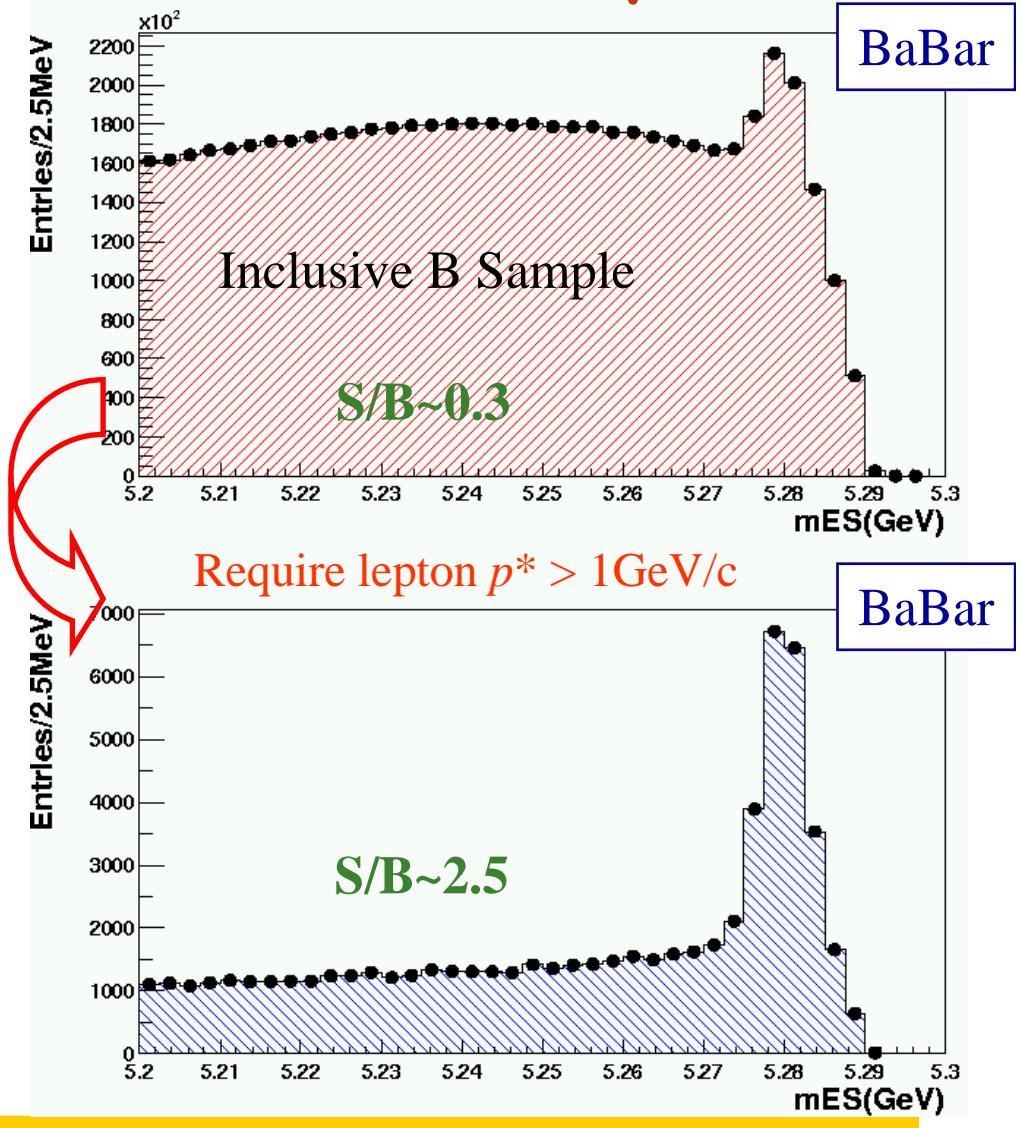
- Possible to achieve  $\sim 5\%$  errors with measurement of inclusive  $b \rightarrow u$  rate
- Would like to be as inclusive as possible; cuts introduce theoretical corrections and model dependence
- Experimentally, have to separate  $b \rightarrow u$  transition from the copious  $b \rightarrow c$  background
  - Electron energy spectrum
  - Hadronic invariant mass cuts
  - Leptonic  $q^2$  selection
  - Mixed cuts



# Fully Reconstructed B Sample

BaBar “semi-exclusive”  
reconstruction: fully reconstruct  
 $B$  mesons in  $\sim 1000$  open charm  
modes

Efficiency  $\sim 0.4\%$  or  $\sim 4000$   
 $B$  mesons/ $\text{fb}^{-1}$  (charged and  
neutral)



Statistical power of B Factories:

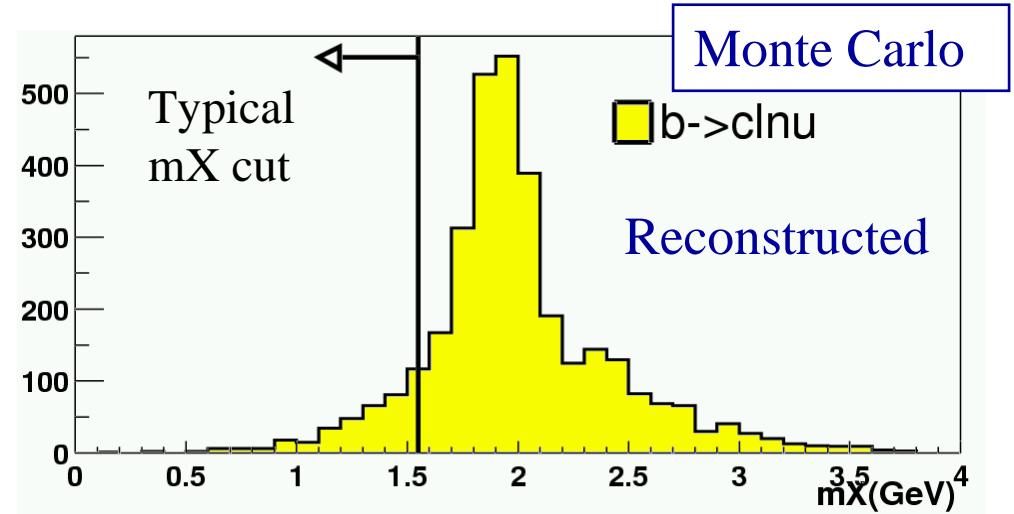
$\sim 330000$  events tagged with fully  
reconstructed  $B$  meson now

Expected by 2006: 2,000,000 events

# Recoil Sample for $b \rightarrow u$ Studies

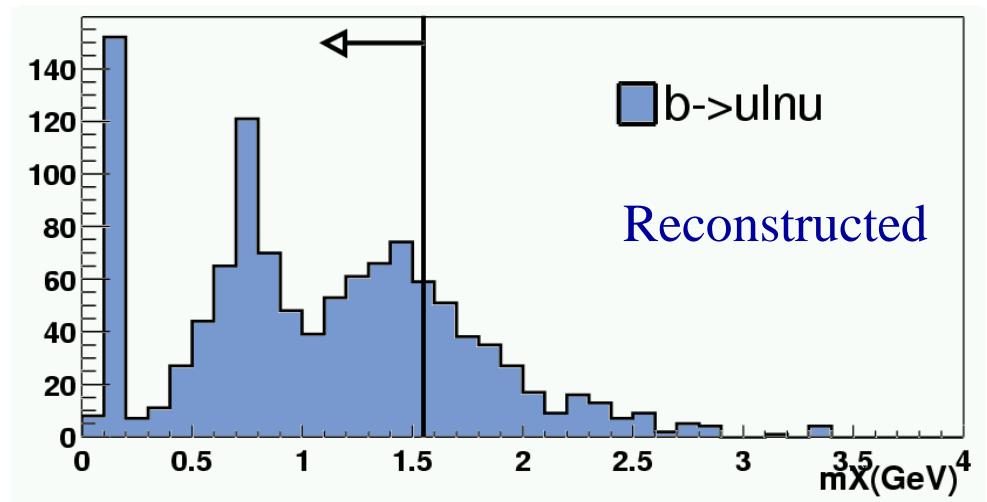
BaBar event selection:

- $B_{\text{recoil}}$  and lepton with  $p>1$  GeV
- Missing mass  $<0.5$  GeV $^2$
- Charge conservation  $Q_{\text{tot}}=0$
- 2-C kinematic fit to improve hadronic mass resolution



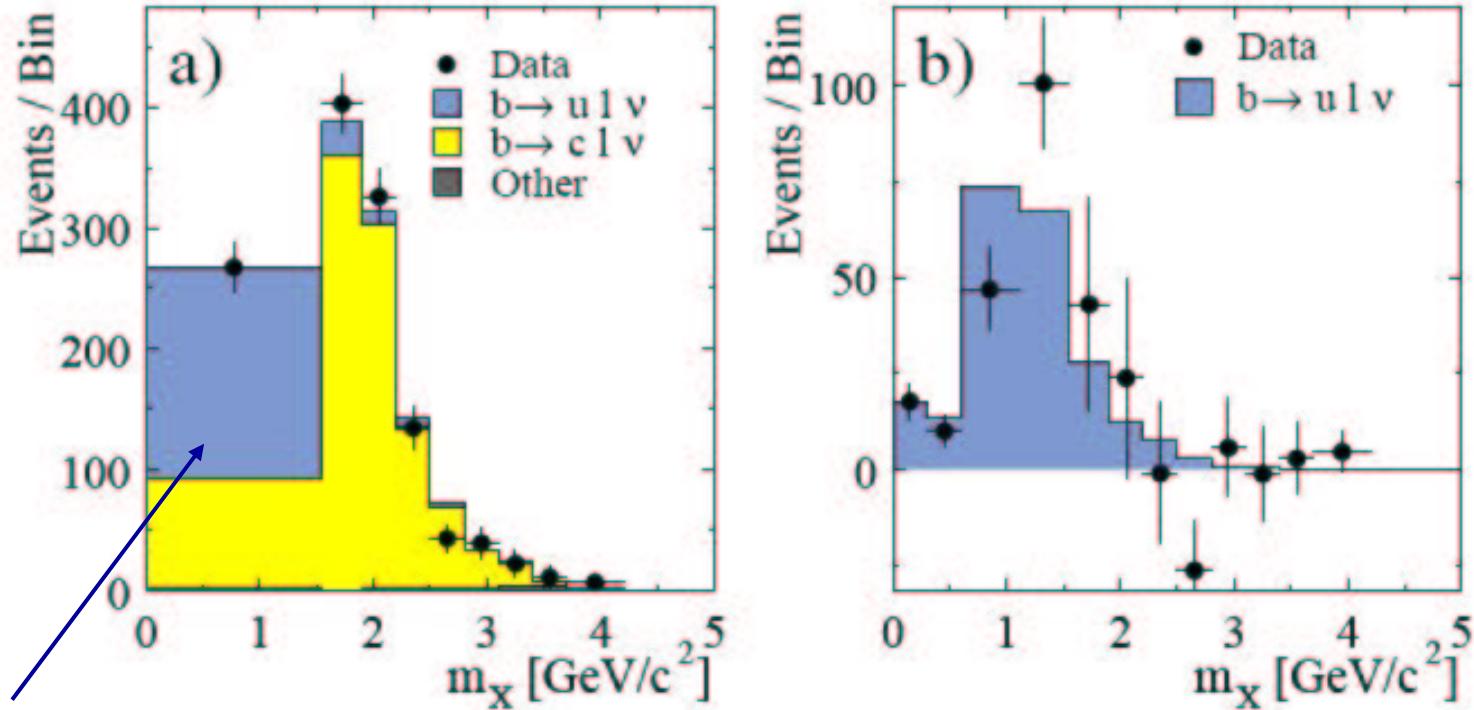
Signal enriched sample: no  $K^\pm, K_S$   
→ Used for the signal fit

Signal depleted sample:  $\geq 1 K^\pm, K_S$   
→ Control sample



# BaBar Results

$b \rightarrow u$  enhanced sample

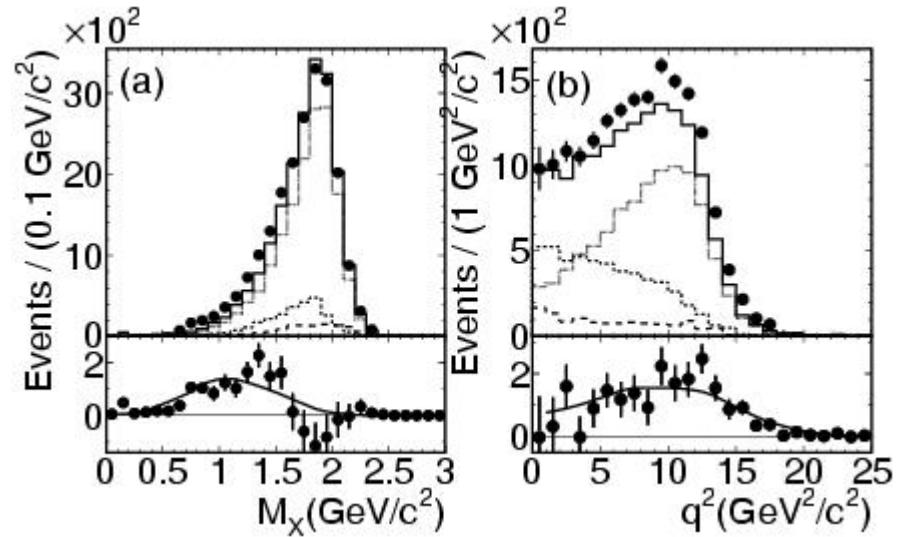


$214 \pm 26$  signal events for  $M_X < 1.7$  GeV

$$|V_{ub}| = 4.62 \pm 0.28 \text{ (stat.)} \pm 0.27 \text{ (syst.)} \pm 0.40 \text{ (extrap.)} \pm 0.26 \text{ (theo.)}$$

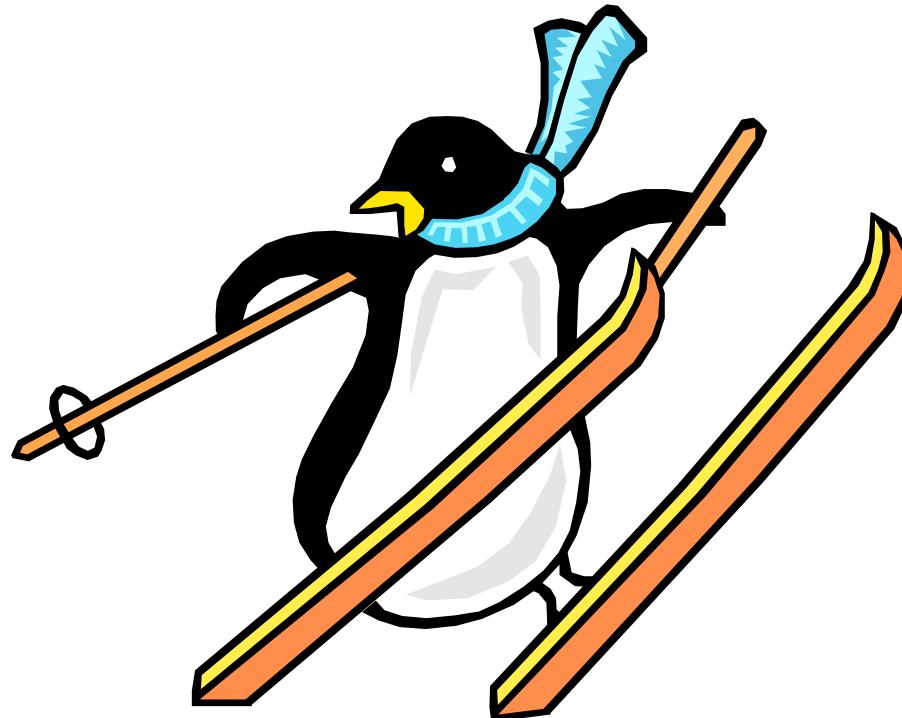
# Belle Results

- Inclusive  $V_{ub}$  with neutrino reconstruction
  - Uses technique of “simulated annealing” to separate decay products of two B mesons
  - Reconstructs neutrino kinematics via missing mass
  - Measures  $M_X$  and  $q^2$  simultaneously
  - Select events with  $M_X < 1.7$  GeV and  $q^2 > 8$  GeV $^2$



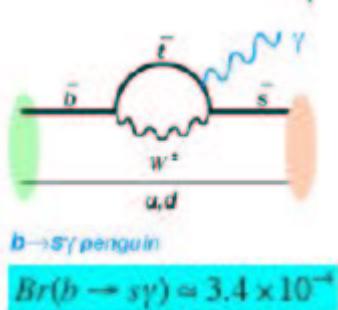
$$|V_{ub}| = 4.66 \pm 0.28 \text{ (stat.)} \pm 0.35 \text{ (syst.)} \pm 0.17 \text{ (model)} \pm 0.08 \text{ (model)} \pm 0.58 \text{ (theo.)}$$

# Electroweak Penguins



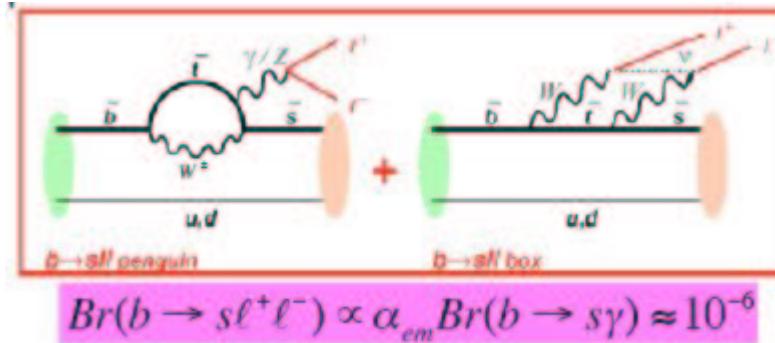
# Electroweak Penguins

- $b \rightarrow s\gamma$  and  $b \rightarrow sl^+l^-$  proceed through FCNC diagrams
  - Suppressed in the Standard Model



$b \rightarrow s\gamma$  penguin

$$Br(b \rightarrow s\gamma) \approx 3.4 \times 10^{-4}$$



$b \rightarrow sll$  penguin

$b \rightarrow sll$  box

$$Br(b \rightarrow sl^+\ell^-) \propto \alpha_{em} Br(b \rightarrow s\gamma) \approx 10^{-6}$$

- Possible New Physics effects in the loops, especially in differential distributions ( $q^2$ ,  $A_{FB}$ )

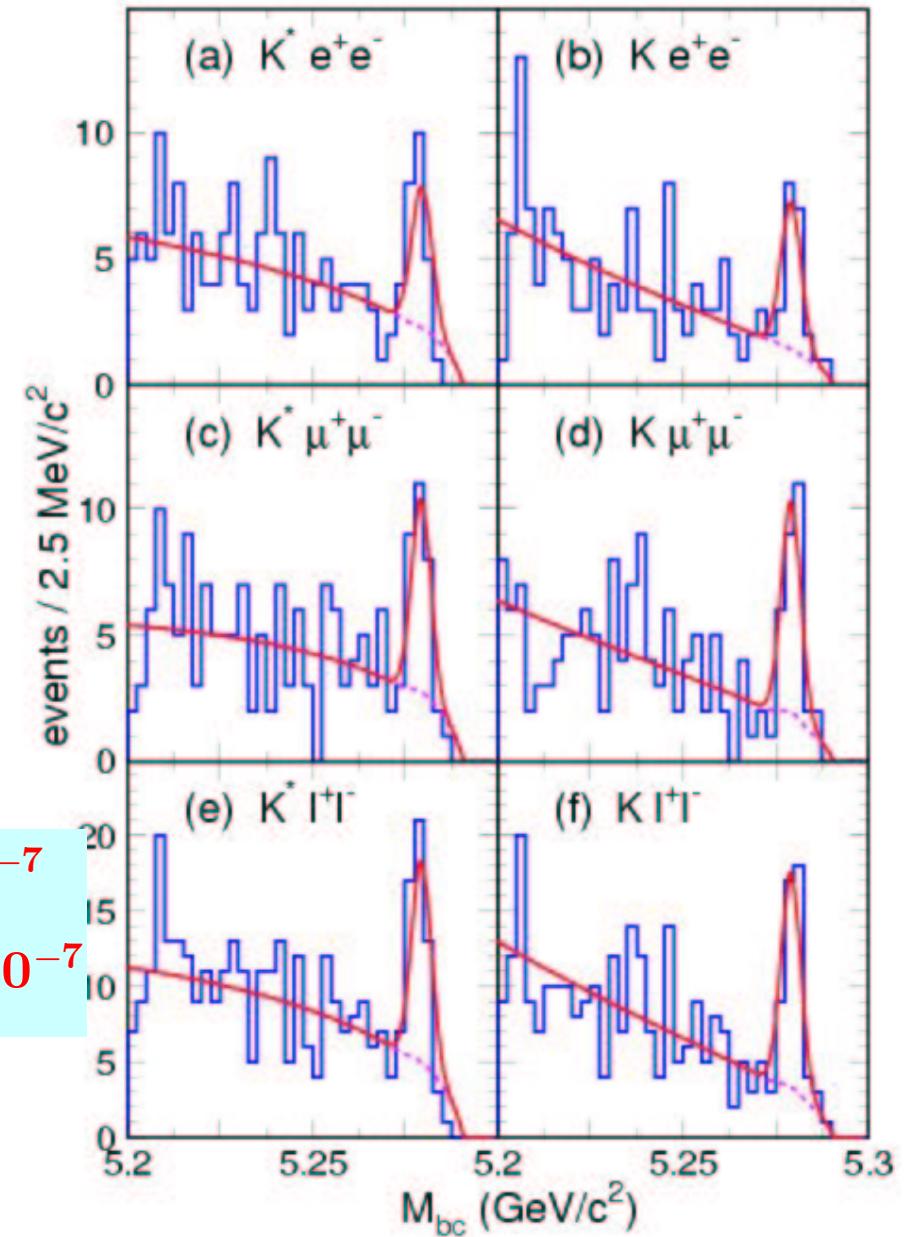
# Belle Results for $B \rightarrow K^{(*)} \ell \ell$

- Updated last summer with  $140 \text{ fb}^{-1}$
- Both charged ( $K^+$  and  $K^{*+} \rightarrow K_S \pi^+, K^+ \pi^0$ ) and neutral ( $K_S$  and  $K^{*0} \rightarrow K^+ \pi^-$ ) modes
- Veto  $J/\Psi, \Psi' \rightarrow l^+ l^-$  candidates

PRL **91**, 261601 (2003)

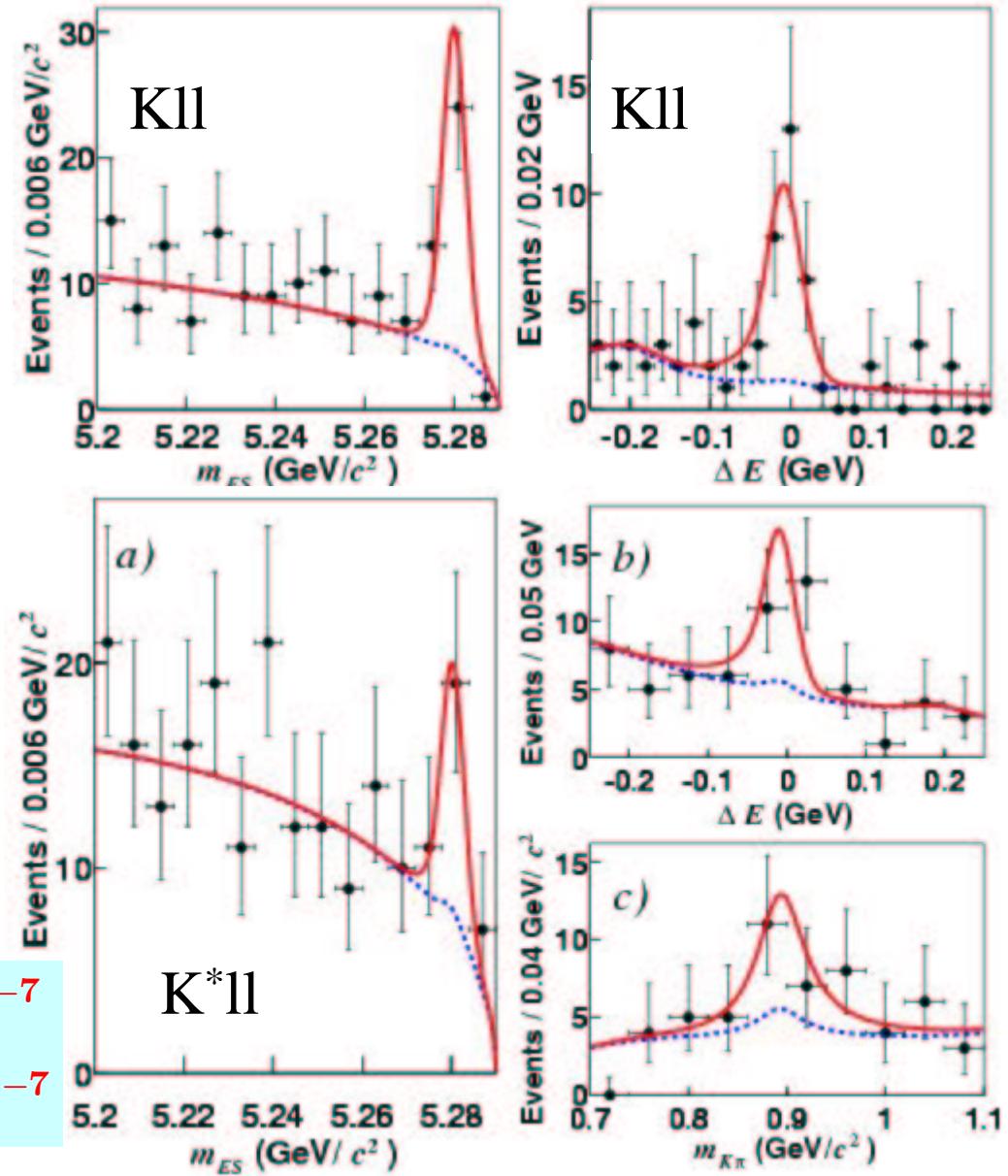
$$\mathcal{B}(B \rightarrow K l^+ l^-) = (4.8_{-0.9}^{+1.0} \pm 0.3 \pm 0.1) \cdot 10^{-7}$$

$$\mathcal{B}(B \rightarrow K^* l^+ l^-) = (11.5_{-2.4}^{+2.6} \pm 0.8 \pm 0.2) \cdot 10^{-7}$$



# BaBar Results for $B \rightarrow K^{(*)} l l$

- Runs 1-3 with  $113 \text{ fb}^{-1}$
- Similar selection to Belle
  - Additional veto for D background due to hadron misID



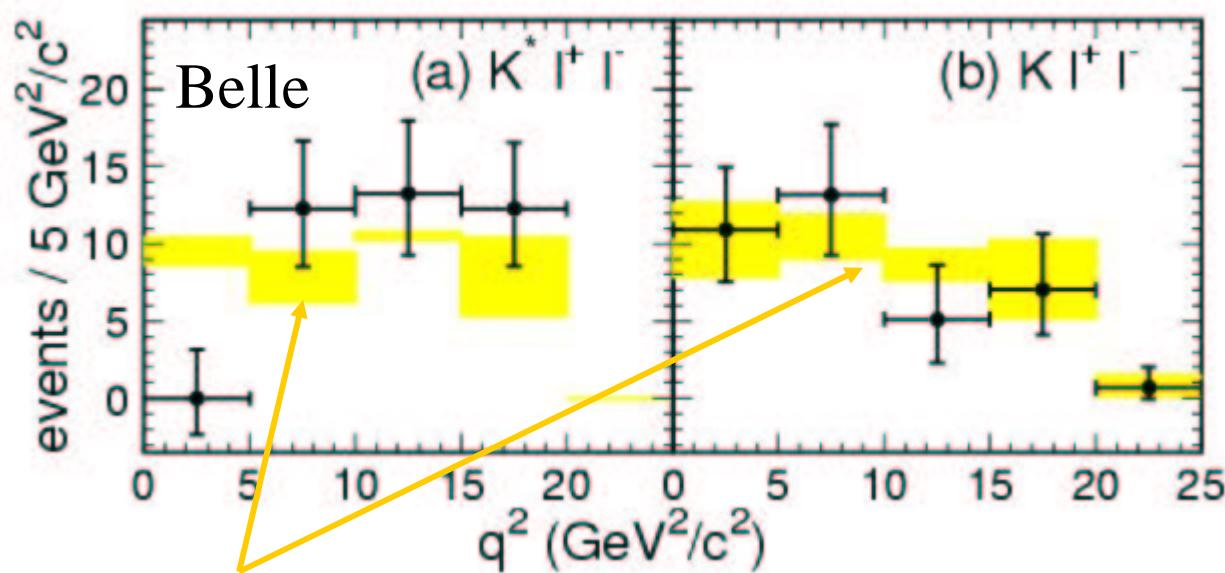
PRL 91, 221802 (2003)

$$\mathcal{B}(B \rightarrow K l^+ l^-) = (6.5^{+1.4}_{-1.3} \pm 0.4) \cdot 10^{-7}$$

$$\mathcal{B}(B \rightarrow K^* l^+ l^-) = (8.8^{+3.3}_{-2.1} \pm 1.0) \cdot 10^{-7}$$

# $q^2$ distribution

- First look at lepton  $q^2$  distribution (Belle) reveals no surprises...
- $A_{FB}$  of lepton pair on deck

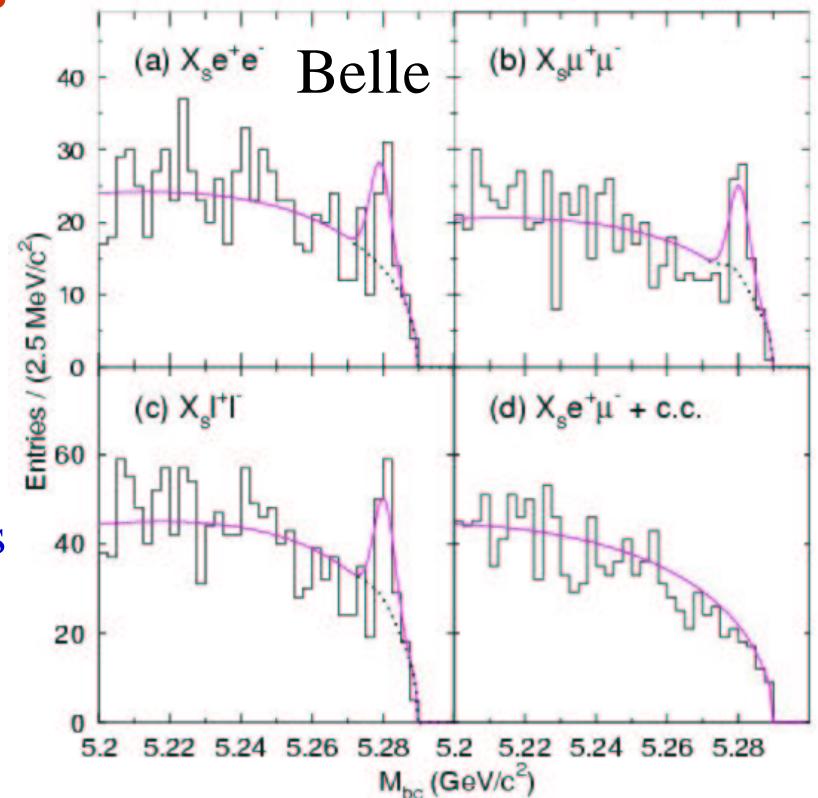


Standard Model expectation

Belle: PRL 91, 261601 (2003)

# Semi-Exclusive Measurement of $B \rightarrow X_s l^+ l^-$

- Inclusive selection of candidates
  - 1  $K^\pm$  or  $K_S$ , plus 0-4 pions (Belle) or 0-2 pions (BaBar), at most one  $\pi^0$
  - $m(X_s) < 2.1$  GeV (Belle),  $< 2.5$  GeV (BaBar)
  - Muon or electron pair, vetoed for charmonium or charm background
- Rate consistent with exclusive measurements and SM, no evidence for LFV process  
 $B \rightarrow X_s e\mu$

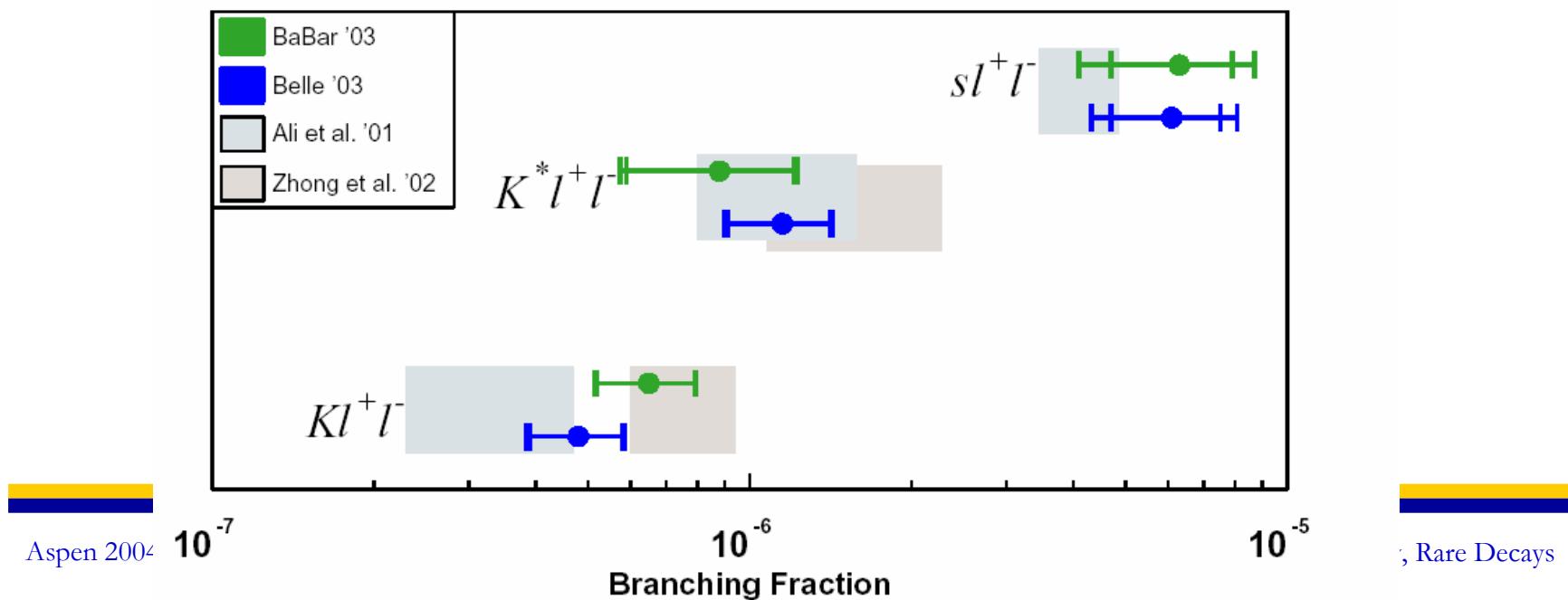


$$\mathcal{B}(B \rightarrow X_s l^+ l^-) = (6.1 \pm 1.4^{+1.4}_{-1.1}) \cdot 10^{-6} \quad (\text{Belle, } 60/\text{fb})$$

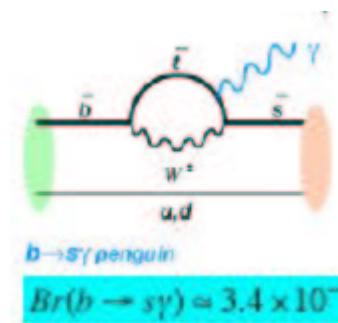
$$\mathcal{B}(B \rightarrow X_s l^+ l^-) = (6.3 \pm 1.6^{+1.8}_{-1.5}) \cdot 10^{-6} \quad (\text{BaBar preliminary, } 80/\text{fb})$$

# Summary of $b \rightarrow s l \bar{l}$ Results

- Clearly established signal
- Branching fractions consistent with the Standard Model within the current level of accuracy
  - Current level of uncertainty at 20% for  $B \rightarrow K l \bar{l}$  and 40% for  $B \rightarrow K^* l \bar{l}$
  - Potential sensitivity to new physics in differential distributions



# $b \rightarrow s\gamma$

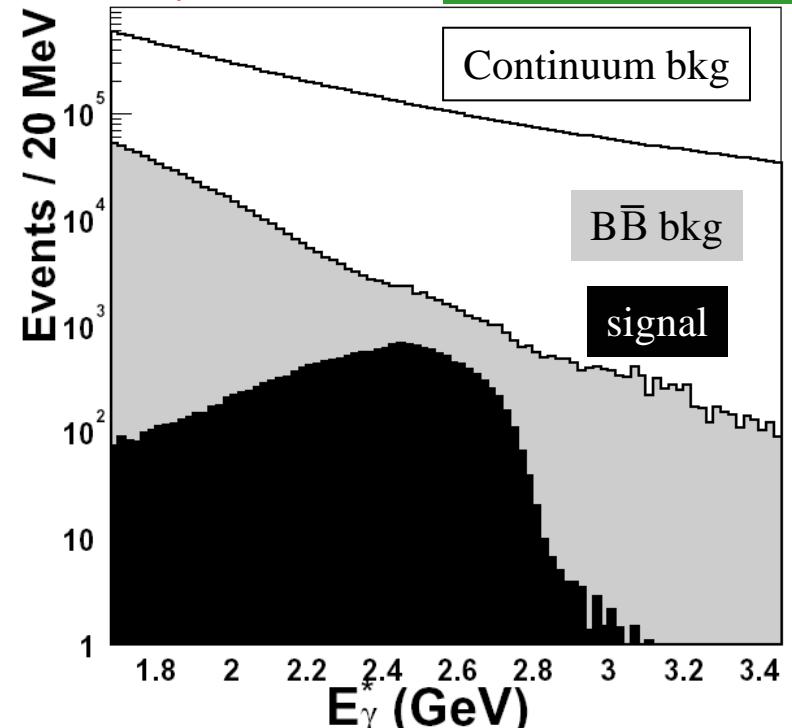


- Sister mode to  $b \rightarrow s\ell\bar{\ell}$
- Energy spectrum a clean measure of non-perturbative B meson dynamics (shape functions)
  - Input to Vub measurements with inclusive  $b \rightarrow u\bar{v}\gamma$  reconstruction
- Direct CP asymmetries sensitive to new physics in the loops
  - SM expectation  $A_{CP} \sim 0.005$  (e.g. Hurth et al., hep-ph/0312260)

# Inclusive $b \rightarrow s\gamma$

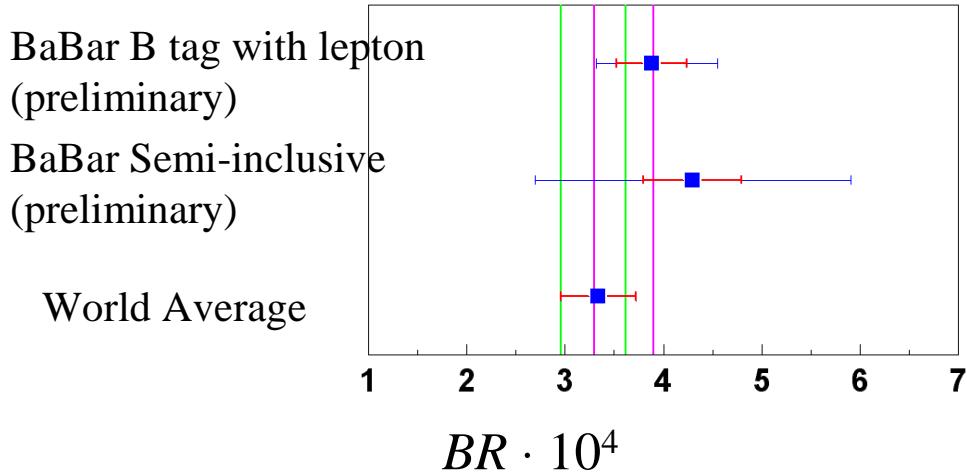
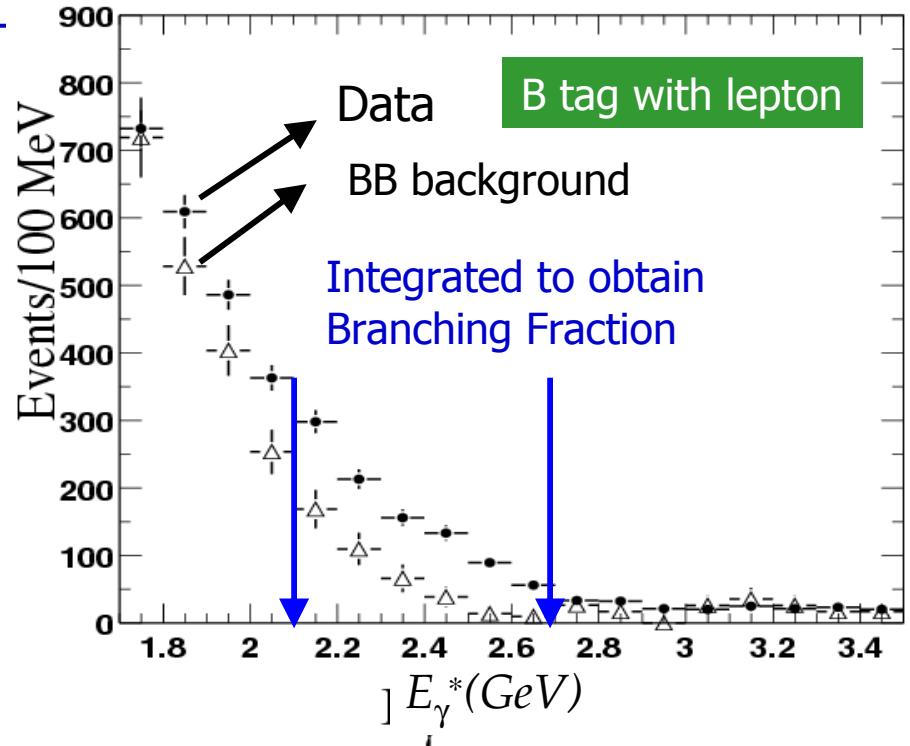
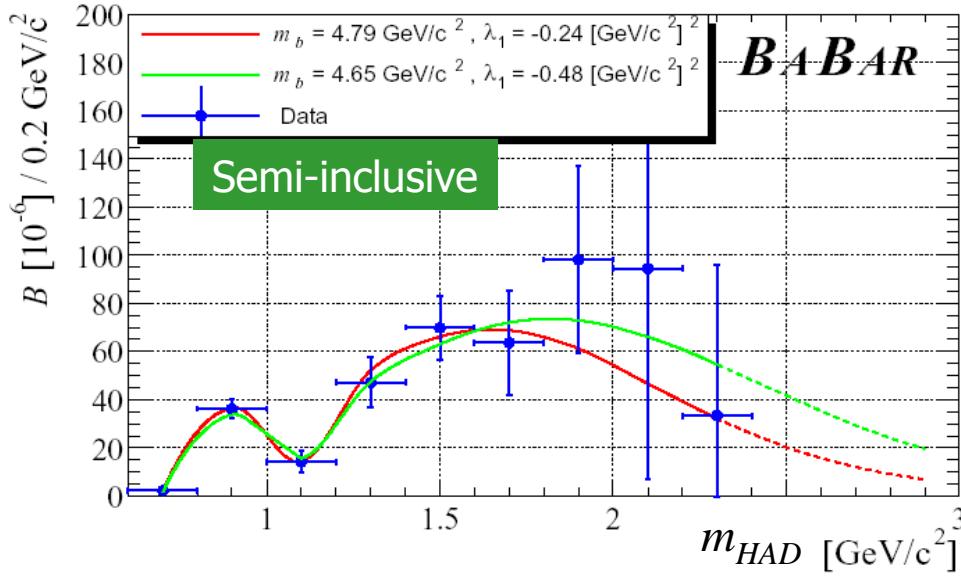
Loose selection

- Pioneered by CLEO (1993)
  - $E_\gamma$  over huge bkg (from non  $B\bar{B}$  pairs)
  - $\pi^0, \eta$  backgrounds from B decays
- Two issues in extracting  $BR(B \rightarrow X_s \gamma)$ 
  - Subtract  $B \rightarrow X_d \gamma$
  - Correct inefficiency due to  $E_\gamma$  cut



- Two different techniques:
  - ✓ **Semi-inclusive** : reconstruct 12 exclusive modes, obtain a hadronic mass spectrum with theoretical shape fcns → extract  $E_\gamma$  moments and  $BR$
  - ✓ **Inclusive  $\gamma$  measurement**: B tag with lepton
    - require  $E_\gamma > 2.1$  GeV
    - require a high momentum lepton (from the other B)

# BaBar Results



$$(3.88 \pm 0.36 \pm 0.37 {}^{+0.43}_{-0.23}) \times 10^{-4}$$

$$(4.3 \pm 0.5 \pm 0.8 \pm 1.3) \times 10^{-4}$$

$$(3.34 \pm 0.38) \times 10^{-4}$$

C.Jessop SLAC-PUB-9610 including CLEO/Belle/ALEPH

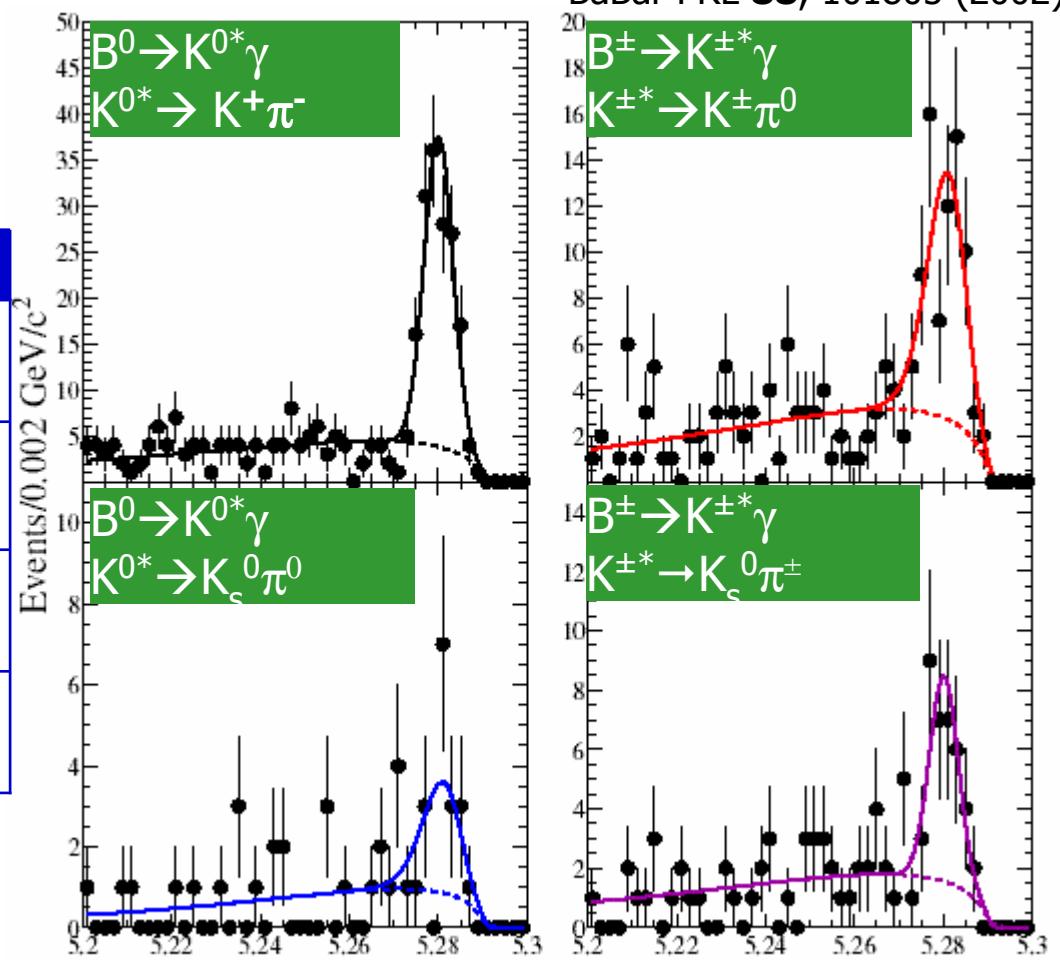
# Exclusive Radiative Decays ( $B \rightarrow K^*\gamma$ )

Clean experimental signal but  
large theoretical errors for  $BR$   
predictions

Mode	$BR \times 10^5$
$B^0 \rightarrow K^* \gamma$	$4.23 \pm 0.40$ (stat) $\pm 0.22$ (syst) (BaBar)
$B^0 \rightarrow K^* \gamma$	$4.09 \pm 0.21$ (stat) $\pm 0.19$ (syst) (Belle)
$B^\pm \rightarrow K^\pm \gamma$	$3.83 \pm 0.62$ (stat) $\pm 0.22$ (syst) (BaBar)
$B^\pm \rightarrow K^\pm \gamma$	$4.40 \pm 0.33$ (stat) $\pm 0.24$ (syst) (Belle)

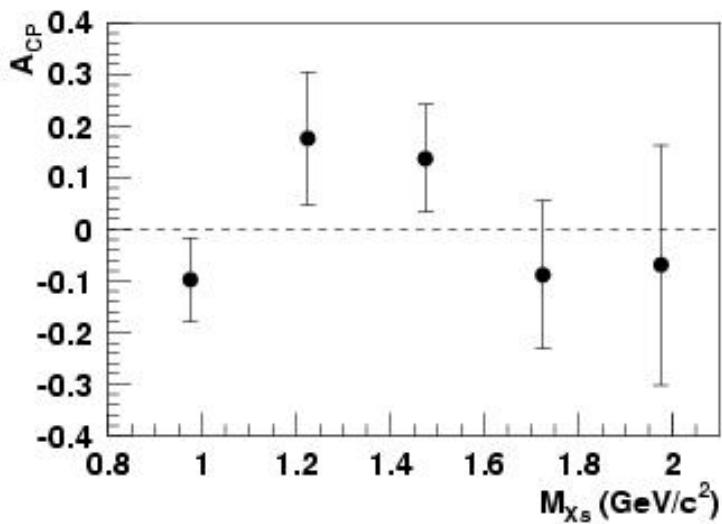
Bosch and Buchalla (hep-ph/0106081):  
SM predicts  $BR \sim (7 \pm 2) \times 10^{-5}$ ,  $A_{CP} < 1\%$

$B \rightarrow K_2(1430)\gamma$  also seen by both BaBar and Belle



# Direct CP Asymmetries in $B \rightarrow X_s \gamma$

- Both exclusive ( $B \rightarrow K^* \gamma$  by BaBar and Belle) and inclusive (Belle) measurements
- Inclusive:
  - $X_s$  system with mass up to 2.1 GeV reconstructed as a sum of exclusive modes  $Kn\pi$  ( $n \leq 4$ ),  $KKK(\pi)$
  - Includes  $K^* \gamma$  as well as  $K\phi\gamma$
  - Analysis based on  $140 \text{ fb}^{-1}$  (Belle, 2003)



Inclusive result (Belle preliminary, 2003):

$$A_{CP} = -0.004 \pm 0.051 \pm 0.038$$

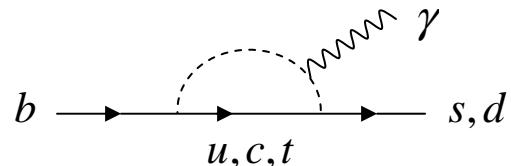
Exclusive measurements ( $K^* \gamma$ ):

$$A_{CP} = -0.044 \pm 0.076 \pm 0.012 \text{ (BaBar, 2002)}$$

$$A_{CP} = -0.001 \pm 0.044 \pm 0.008 \text{ (Belle preliminary, 2003)}$$

# Exclusive Radiative Decays $b \rightarrow d\gamma$

$B \rightarrow \rho(\omega)\gamma$



SM:  $BR \sim 10^{-6}$

- $b \rightarrow d\gamma$  modes:
  - background for inclusive  $b \rightarrow s\gamma$
  - sensitive to  $|V_{td}/V_{ts}|$
  - complementary to  $\Delta m_d/\Delta m_s$

$$\frac{BR(B \rightarrow \rho\gamma)}{BR(B \rightarrow K^*\gamma)} = \frac{1}{2} \left| \frac{V_{td}}{V_{ts}} \right|^2 \frac{(1 - m_\rho^2/m_B^2)^3}{(1 - m_{K^*}^2/m_B^2)^3} \zeta^2 [1 + \Delta R(\rho/K^*)]$$

Ali and Parkhomenko  
EPJ C23 89 (2002)

$\zeta$ : ratio of the form factors

$\Delta R$ : calculated to leading order in  $\alpha_s$  and  $\Lambda_{\text{QCD}}/m_H$

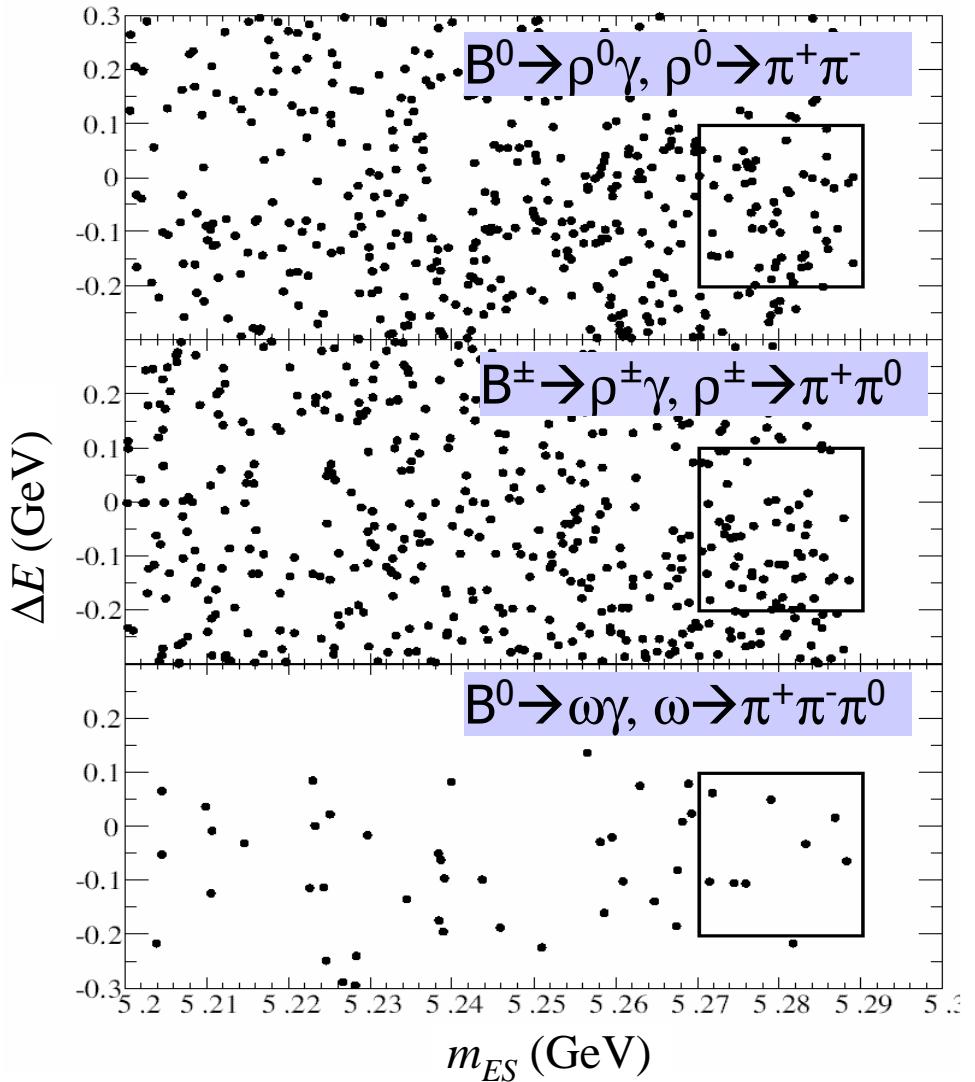
# BaBar Limits on $B \rightarrow \rho(\omega)\gamma$

- Significant continuum background
  - BaBar search: Optimized neural network of event shapes, helicity,  $z$  vertex displacement...
- Kaon rejection from  $B \rightarrow K^*\gamma$  critical
  - 80 % pion efficiency with 1–2 % kaon fake rate

BaBar Preliminary:

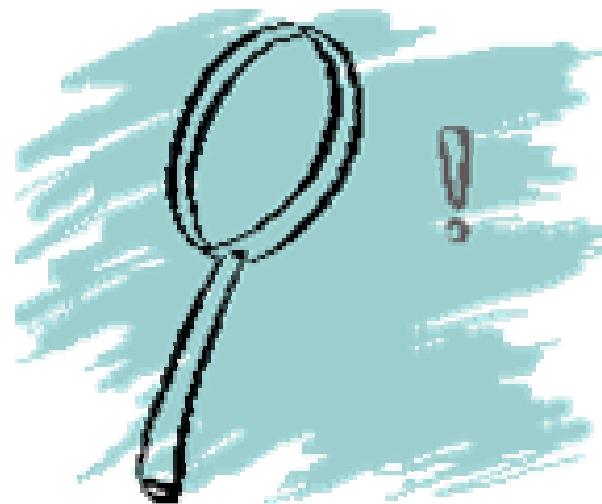
Mode	$BR \times 10^6$
$B^0 \rightarrow \rho^0 \gamma$	< 1.2
$B^\pm \rightarrow \rho^\pm \gamma$	< 2.1
$B^0 \rightarrow \omega \gamma$	< 1.0

No evidence for signal yet,  
but close to SM expectation  
for  $BR \sim 10^{-6}$



BaBar: hep-ex/0306038

# Rare Leptonic Decays

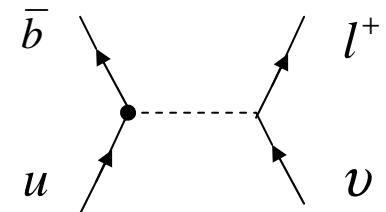


# Leptonic B Decays

$$B^+ \rightarrow l^+ \nu$$

SM: W-annihilation decays with  $V_{ub}$  vertex

$$BR(B^+ \rightarrow l^+ \nu) = \frac{G_F^2 m_B m_l^2}{8\pi} \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

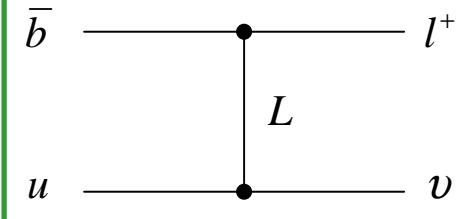


- ✓ BR is very small for  $l = e, \mu$  (helicity suppression)
- ✓  $BR(B \rightarrow \tau \nu) \sim 250$   $BR(B \rightarrow \mu \nu)$  but experimentally more challenging

Clean SM prediction, small BR: a good place look for new physics. For instance:

- charged Higgs Hou, PRD 48 2342 (1993)
- leptoquark Valencia, Willenbrock PRD 50 6843 (1994)

Related decay:  $B^0 \rightarrow l^+ l^-$



# BaBar: Limits on Leptonic Decays

$$B^+ \rightarrow \mu^+ \nu$$

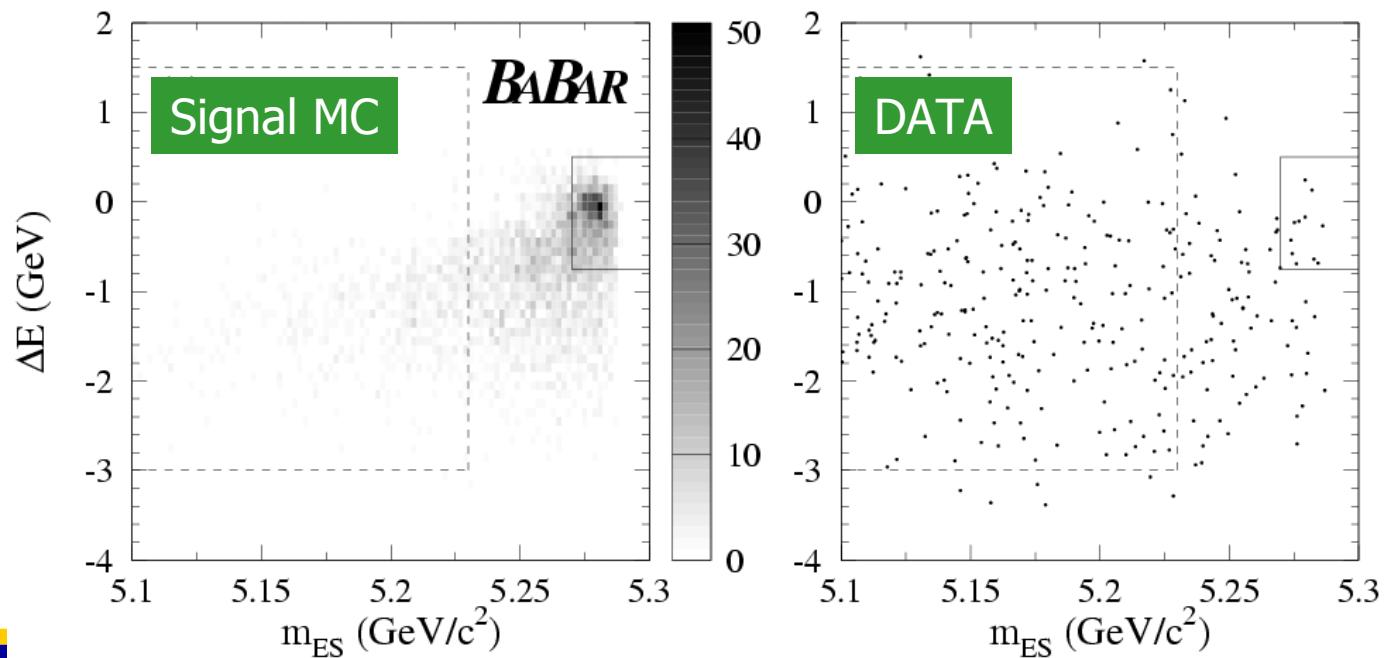
Selection:

- ✓ Event shape cuts
- ✓ Select mono-energetic muons
- ✓  $\Delta E$  and  $m_{ES}$  cuts

$BR(B^+ \rightarrow \mu^+\nu) < 6.6 \times 10^{-6}$  (2003, 81/fb)

SM :  $BR \sim 4 \times 10^{-7}$

11 events over  
BKG =  $5.0^{+1.8}_{-1.4}$



# BaBar: Limits on $B \rightarrow \tau\nu$

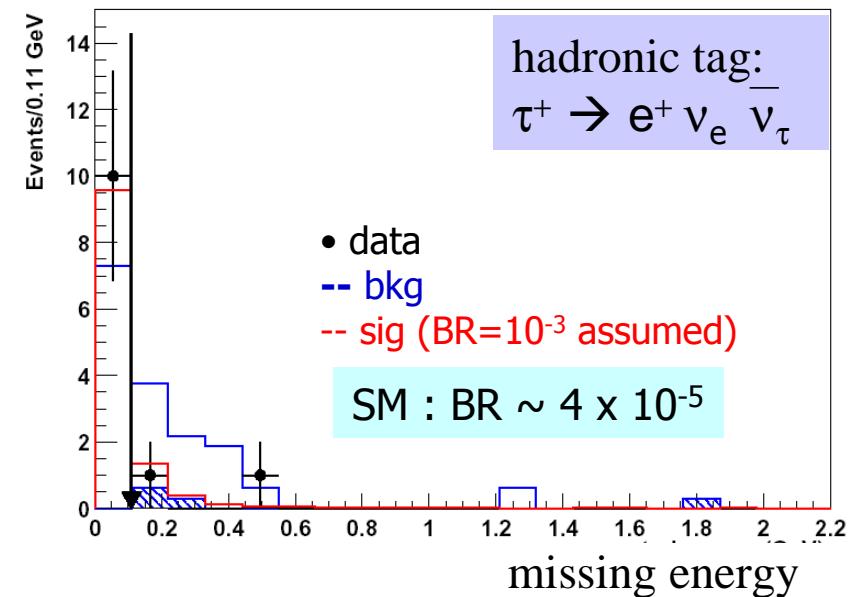
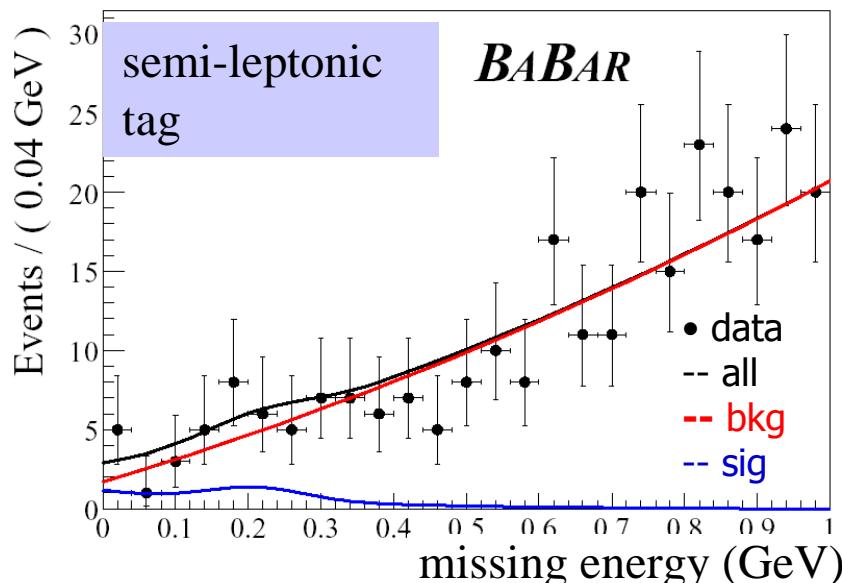
BaBar reconstructs the recoil B by:

$$B^- \rightarrow D^0 l^- \nu + X \quad (\text{semi-leptonic tag})$$

$$B^- \rightarrow D^{(*)0} + n_1 \pi^\pm + n_2 K^\pm + n_3 \pi^0 + n_4 K_s^0 \quad (\text{hadronic tag})$$

And look for  $\tau$  decays of :

hadronic tag	}	$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$	semi-leptonic tag
		$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$	
		$\tau^+ \rightarrow \pi^+ \nu$	
		$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}$	
		$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}$	



# Belle: Limits on Leptonic Decays

- FCNC:  $B^0 \rightarrow l^+ l^-$ 
  - Belle limits (full reconstruction):

Mode	$BR \times 10^7$
$B^0 \rightarrow e^+ e^-$	< 1.9
$B^\pm \rightarrow \mu^+ \mu^-$	< 1.6
$B^0 \rightarrow e \mu$	< 1.7

☞ 46 GeV limit on specific leptoquark models

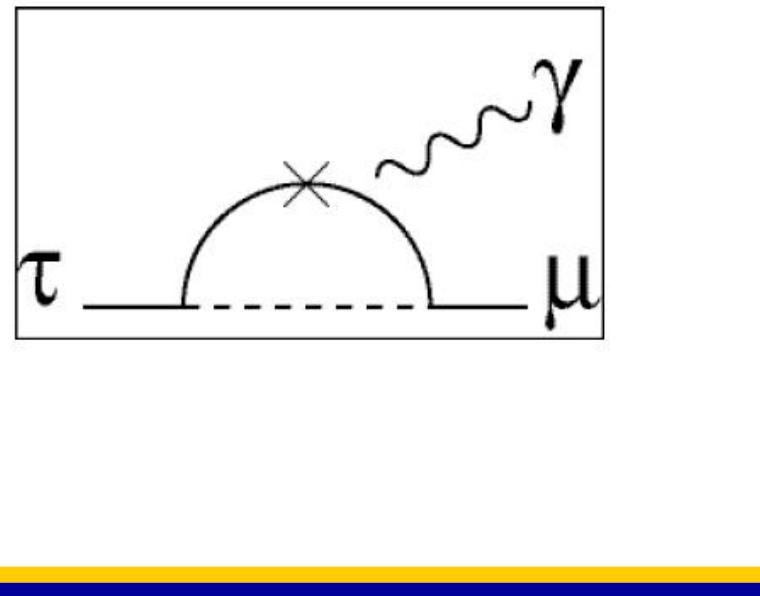
# LPF in Tau Decays



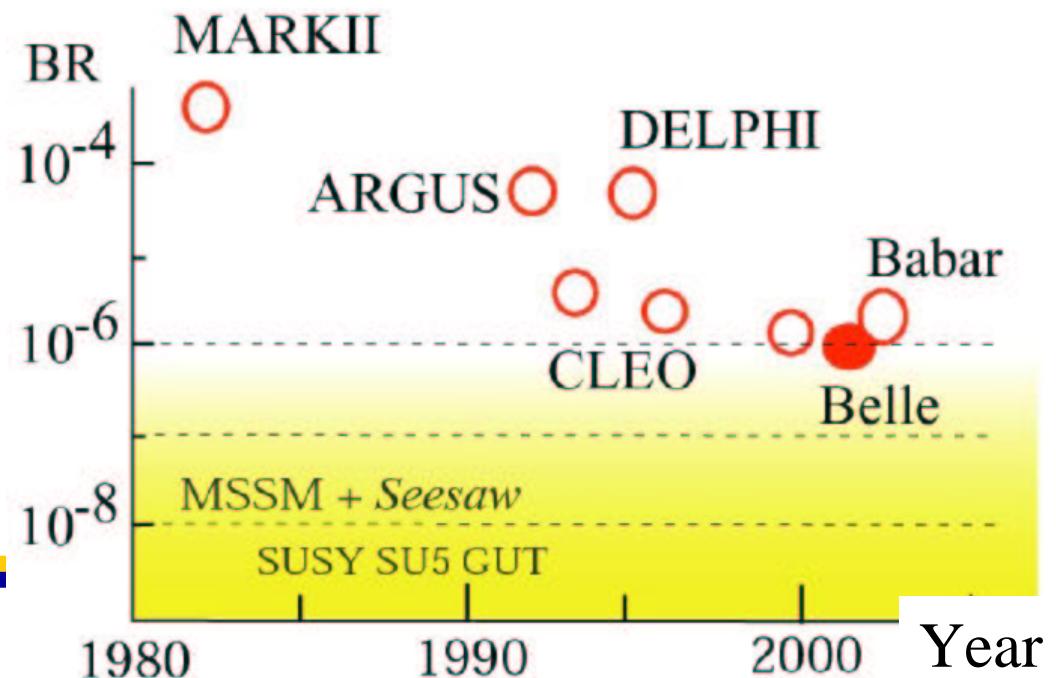
# LFV in Tau Decays

- Large samples of tau decays available in B factories: opportunity for sensitive searches for forbidden SM processes
  - $\tau \rightarrow \mu\gamma$  (BaBar, 2002; Belle, 2003)
  - $\tau \rightarrow lll$  (BaBar, 2003)

Summary of existing limits:

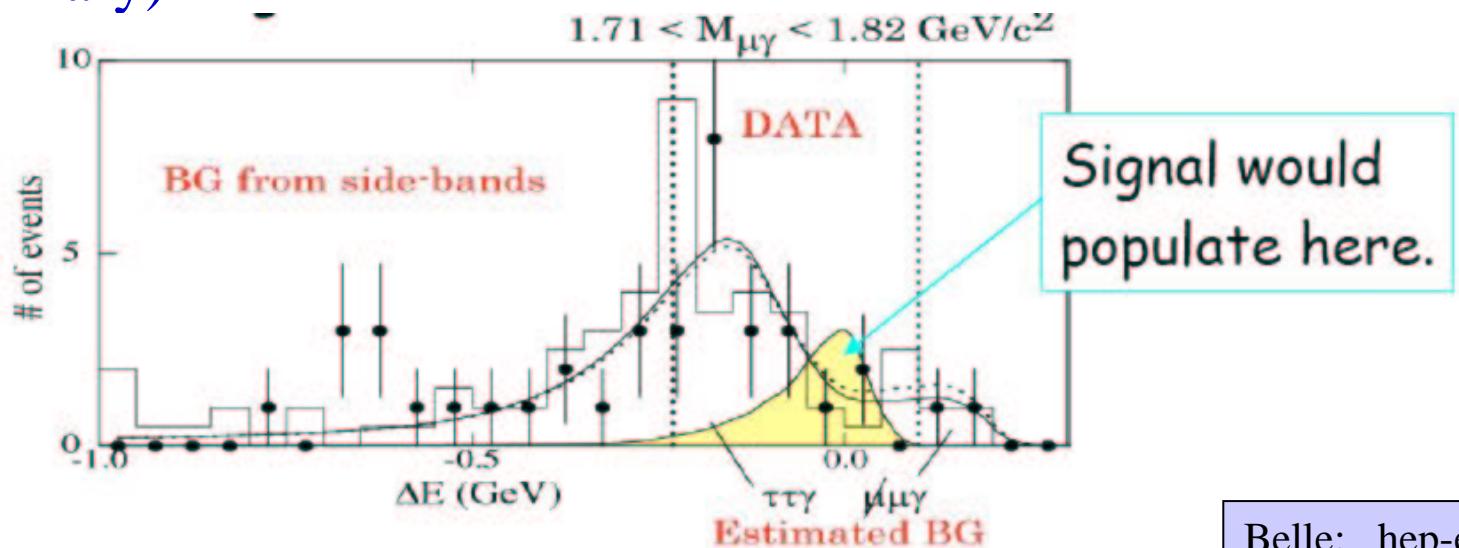
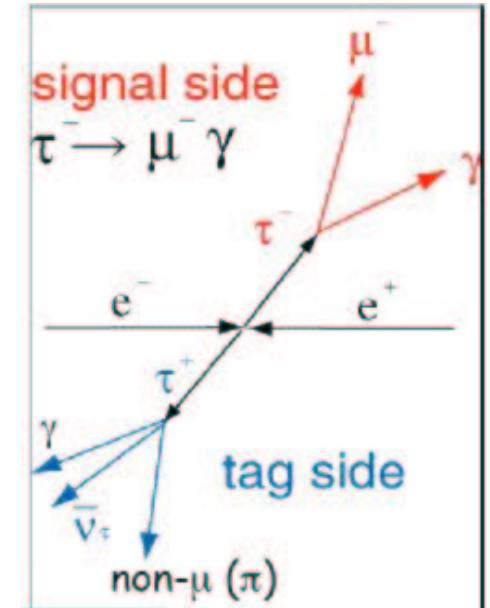


Aspen 2004



# Belle $\tau \rightarrow \mu\gamma$ Search

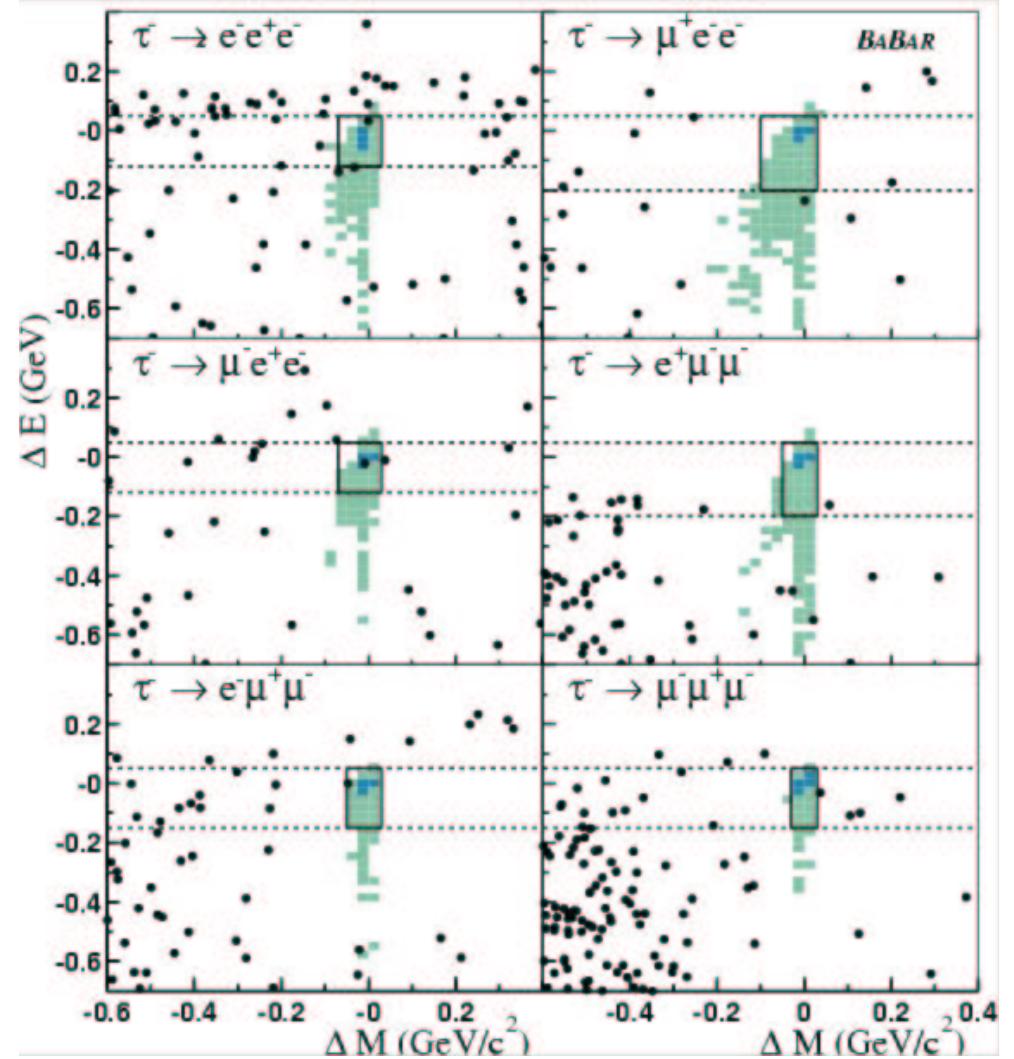
- Select two oppositely charged particles consistent with  $\tau \rightarrow \mu\gamma$  on one side and  $\tau \rightarrow (e,h)\nu + n\gamma$  on the other side
  - Dominant background from radiative (ISR) processes  $e^+e^- \rightarrow \mu\mu\gamma$  and  $e^+e^- \rightarrow \tau\tau\gamma$
  - Require missing neutrino ( $m_{\text{miss}}^2 \sim 0$ )
- Limit  $\text{Br}(\tau \rightarrow \mu\gamma) < 3.2 \cdot 10^{-7}$  (90% CL, 86/fb, preliminary)



Belle: hep-ex/0310029

# BaBar $\tau \rightarrow lll$ Search

- Select 3+1 tau decay topologies
  - 3 leptons (all possible combinations) on one side
  - One track on the other side
  - Missing mass  $\Delta M$  and reconstructed  $\Delta E$  consistent with zero
- 3 events seen, consistent with background expectations
  - $BR(\tau \rightarrow lll) < (1-3) \cdot 10^{-7}$  depending on the mode



# Summary

- High statistics available at B Factories facilitates searches and measurements of rare decays with BR down to  $10^{-7}$ 
  - CKM suppressed B decays
  - Electroweak penguins
  - Leptonic B decays
  - Tau decays
- As statistics is expected to triple in the next few years, sensitivities will start approaching the region of interest for a wide range of new physics models
  - ☞ Targets of opportunity for future experiments